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Short-baseline electron neutrino oscillation length after the Troitsk experiment

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We discuss the implications for short-baseline electron neutrino disappearance in the 3 + 1 mixing scheme of the recent Troitsk bounds on the mixing of a neutrino with mass between 2 and 100 eV. Considering the Troitsk data in combination with the results of short-baseline ν_e and $\bar{\nu}_e$ disappearance experiments, which include the reactor and Gallium anomalies, we derive a 2σ allowed range for the effective neutrino squared-mass difference between 0.85 and 43 eV^2. The upper bound implies that it is likely that oscillations in distance and/or energy can be observed in radioactive source experiments. It is also favorable for the ICARUS@CERN experiment, in which it is likely that oscillations are not washed out in the near detector. We discuss also the implications for neutrinoless double-β decay.

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The reactor $\bar{\nu}_e$ [1–3] and the Gallium ν_e [4–6] anomalies indicate that electron neutrino and antineutrinos may disappear at short distances because of oscillations generated by a squared-mass difference $\Delta m^2_{\mathrm{SBL}} \gtrsim 1\ \mathrm{eV}^2$ [4–7]. Since $\Delta m^2_{\mathrm{SBL}}$ is much larger than the two Δm^2's which generate the observed solar, atmospheric and long-baseline oscillations in standard three-neutrino mixing (see Refs. [8–10]), we are led to consider the so-called 3 + 1 neutrino mixing scheme, which is the extension of standard three-neutrino mixing with an additional massive neutrino. This is the simplest extension of standard three-neutrino mixing that can explain the reactor and Gallium anomalies. In the flavor basis, the additional neutrino is sterile, because from the LEP measurement of the invisible width of the Z boson [11], we know that there are only three light active flavor neutrinos, ν_e, ν_μ and ν_τ. Hence, we have the mixing relation

$$\nu_\alpha = \sum_{k=1}^{4} U_{\alpha k} \nu_k \qquad (\alpha = e, \mu, \tau, s) \tag{1}$$

between the flavor fields ν_α (ν_s is the sterile neutrino) and the massive fields ν_k, with respective masses m_k. U is the unitary 4×4 mixing matrix. The effective survival probability at a distance L of electron neutrinos and antineutrinos with energy E in short-baseline (SBL) neutrino oscillation experiments is given by (see Refs. [12–15])

$$P^{\mathrm{SBL}}_{\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e} = 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), \tag{2}$$

with $\Delta m^2_{41} \equiv m^2_4 - m^2_1 = \Delta m^2_{\mathrm{SBL}}$ and the transition amplitude

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2). \tag{3}$$

In Ref. [7] we presented an update of the 3 + 1 analysis of short-baseline ν_e and $\bar{\nu}_e$ disappearance experiments[1] which took into account (1) the data of the Bugey-3 [23], Bugey-4 [24], ROVNO91 [25], Gosgen [26], ILL [27] and Krasnoyarsk [28] reactor antineutrino experiments, with the new theoretical fluxes [1–3], (2) the data of the GALLEX [29–31] and SAGE [32–35] Gallium radioactive source experiments with the statistical method discussed in Ref. [6], considering the recent ${}^{71}\mathrm{Ga}({}^{3}\mathrm{He}, {}^{3}\mathrm{H}){}^{71}\mathrm{Ge}$ cross-section measurement in Ref. [36], (3) the solar neutrino constraint on $\sin^2 2\vartheta_{ee}$ [7,37–40], and (4) the KARMEN [41,42] and LSND [43] $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N}_{\mathrm{g.s.}} + e^-$ scattering data [44], with the method discussed in Ref. [45]. In Fig. 1 we reproduce the allowed 95% confidence level (CL) region in the $\sin^2 2\vartheta_{ee}$-Δm^2_{41} plane presented in Ref. [7]. One can see that there is no upper limit for Δm^2_{41} from oscillation data. In Ref. [7] we discussed the possibilities to constrain $\sin^2 2\vartheta_{ee}$ and Δm^2_{41} with measurements of the effects of m_4 on the electron spectrum in β decay far from the end point and with neutrinoless

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[1] We do not consider here, or in Ref. [7], the more controversial LSND [16] and MiniBooNE [17] $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ anomalies, whose explanation in the framework of neutrino oscillations is problematic (see Refs. [18–22]).

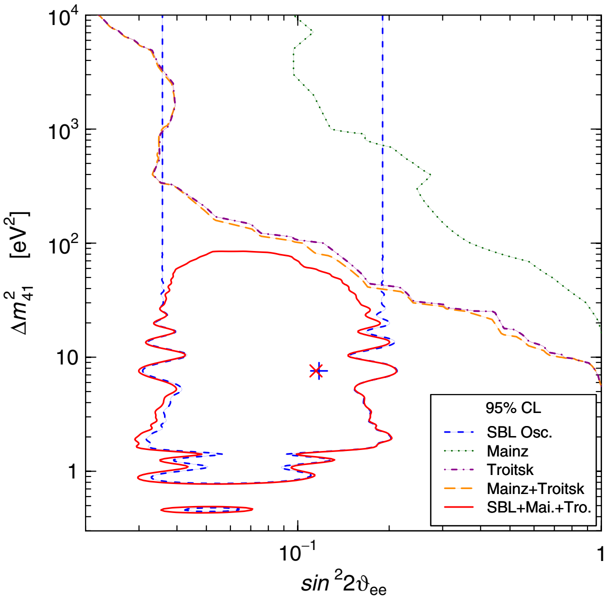

FIG. 1 (color online). Comparison of the 95% CL allowed region in the $\sin^2 2\vartheta_{ee}$-Δm^2_{41} plane obtained from the global fit of ν_e and $\bar{\nu}_e$ short-baseline oscillation data [7], the 95% CL bounds obtained from Mainz [49] and Troitsk [50] data, and the allowed region obtained from the combined fit. The best-fit points of the oscillation and combined analyses are indicated, respectively, by "+" and "×".

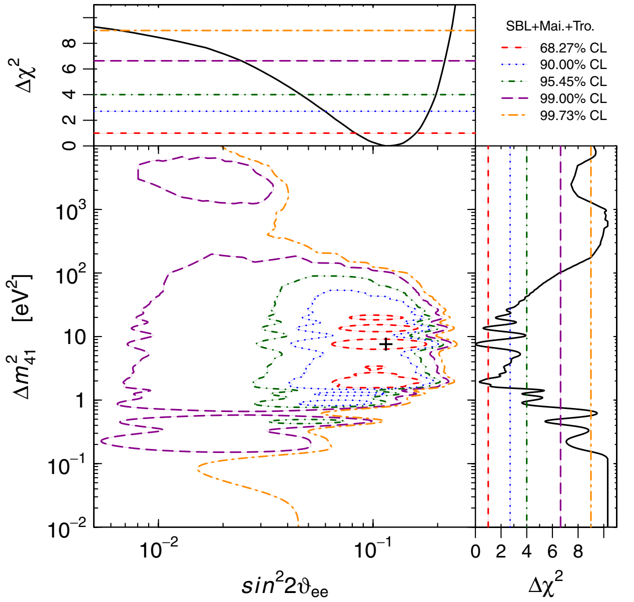

FIG. 2 (color online). Allowed regions in the $\sin^2 2\vartheta_{ee}$-Δm^2_{41} plane and marginal $\Delta\chi^2$'s for $\sin^2 2\vartheta_{ee}$ and Δm^2_{41} obtained from the combined fit of ν_e and $\bar{\nu}_e$ short-baseline oscillation data and the data of the Mainz [49] and Troitsk [50] experiments. The best-fit point is indicated by a "+".

double-β decay (if massive neutrinos are Majorana particles)[2] assuming the natural mass hierarchy

$$m_1, m_2, m_3 \ll m_4, \tag{4}$$

which implies

$$m_4^2 \simeq \Delta m^2_{41}. \tag{5}$$

In particular, we showed that the recent Tritium β-decay data of the Mainz Neutrino Mass Experiment [49] constrain Δm^2_{41} to be smaller than about 10^4 eV^2 at 95% CL.

Recently the Troitsk Collaboration presented the results [50] of a search for the effects of m_4^2 between 4 and 10^4 eV^2 in the spectrum of the electrons emitted in tritium decay in the Troitsk nu-mass experiment. Since they did not find any deviation from the massless neutrino case, their data allowed them to constrain the value of $|U_{e4}|^2$ as a function of m_4^2 in a similar way as done by the Mainz Collaboration. Since the Troitsk bounds are significantly stronger than the Mainz bounds, in this paper we present an update of the analysis in Ref. [7], which takes into account the Troitsk data.

Figure 1 shows the 95% CL exclusion curves in the $\sin^2 2\vartheta_{ee}$-Δm^2_{41} plane obtained with the Mainz and Troitsk data. One can see that the Troitsk exclusion curve cuts the region allowed at 95% CL by short-baseline oscillation data for values of Δm^2_{41} between about 40 and 400 eV^2. In this interval of Δm^2_{41} the Troitsk upper bound on $\sin^2 2\vartheta_{ee}$ is from about four to six times more stringent than that of Mainz. For completeness, in Fig. 1 we have shown also the combined Mainz and Troitsk exclusion curve, but one can see that the improvement with respect to the Troitsk exclusion curve is very small.

The allowed region in Fig. 1 obtained from the combined fit of short-baseline oscillation data and Mainz and Troitsk data shows that the value of Δm^2_{41} is bounded from above. Figure 2 shows the combined allowed regions in the $\sin^2 2\vartheta_{ee}$-Δm^2_{41} plane at different CL's and the marginal $\Delta\chi^2 = \chi^2 - \chi^2_{\text{min}}$'s for $\sin^2 2\vartheta_{ee}$ and Δm^2_{41}.

In order to get an estimate of the allowed range of Δm^2_{41}, we consider the corresponding marginal $\Delta\chi^2$, which gives

$$0.85 \lesssim \Delta m^2_{41} \lesssim 43 \text{ eV}^2 \qquad (2\sigma). \tag{6}$$

This is a very interesting range, because it implies that the oscillation length $L^{\text{osc}}_{41} = 4\pi E/\Delta m^2_{41}$ is in the interval

$$6 \text{ cm} \lesssim \frac{L^{\text{osc}}_{41}}{E[\text{MeV}]} \lesssim 3 \text{ m} \qquad (2\sigma). \tag{7}$$

Taking into account that electron neutrino and antineutrino radioactive sources have a typical size of a few centimeters, there are good possibilities that new experiments with these sources [47,51–58] can measure the dependence of the disappearance probability as a function of distance and/or energy. Such a measurement will be a smoking-gun

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[2] Let us only mention that cosmological measurements give information on the number of neutrinos and on the values of neutrino masses at the eV scale (see Refs. [46–48]), but the results depend on the theoretical assumption of a cosmological model.

proof of short-baseline oscillations and of the existence of light sterile neutrinos.

For radioactive source experiments using electron neutrinos produced by electron capture, which have a discrete spectrum, the oscillatory pattern of the survival probability can be observed if the detector has a spatial resolution that is much smaller than the oscillation length, i.e., much smaller than 6 cm if L_{41}^{osc} is close to the lower bound in Eq. (7). In this case, the sensitivity to oscillations could be enhanced by using a very thin source in one or two spatial dimensions (for example, a long and thin cylinder or a flat rectangular parallelepiped). Then, if L_{41}^{osc} is close to the lower bound in Eq. (7), one could observe an interesting three-dimensional pattern in which the average survival probability oscillates as a function of distance along the thin direction(s) and does not depend on distance along the thick direction(s).

Experiments using radioactive β^- sources of electron antineutrinos with a continuous spectrum can measure also the oscillatory pattern of the survival probability as a function of energy if the spatial resolution of the detector is smaller than the oscillation length and if the energy resolution ΔE is such that

$$\Delta E/E \ll L_{41}^{\text{osc}}/L. \tag{8}$$

Since electron antineutrinos are detected with the inverse neutron decay reaction $\bar{\nu}_e + p \to n + e^+$ with a threshold of 1.8 MeV, if L_{41}^{osc} is close to the lower bound in Eq. (7), a spatial resolution much smaller than 10 cm and an energy resolution much better than 10% at $L \sim 1$ m are needed.

The proposed ICARUS@CERN experiment [59–61] is based on two liquid-argon time-projection-chamber imaging detectors at 300 m and 1.6 km from the source. Since the beam will have an average neutrino energy of about 2 GeV, the oscillation length is larger than the distance of the near detector for $\Delta m_{41}^2 \lesssim 20$ eV^2. This upper bound is of the same order as that obtained in Eq. (6). Hence, our results imply that the ICARUS@CERN experiment has good possibilities to measure the disappearance of electron neutrinos if the oscillation interpretation of the reactor and Gallium anomalies is correct, because oscillations are not washed out in the near detector.

There are also several projects aimed at the measurement of the short-baseline disappearance reactor $\bar{\nu}_e$'s [47,62–65]. Taking into account that the product of the reactor $\bar{\nu}_e$ flux and the detection cross section peaks at about 4 MeV, the size of a research reactor is about 50 cm, and a detector cannot be placed closer than a few meters from a reactor, the distance and/or energy dependence of the survival probability may be measured if the upper bound on Δm_{41}^2 is about an order of magnitude smaller than that in Eq. (6). Such restriction[3] may come from the results of the KATRIN experiment [67–70].

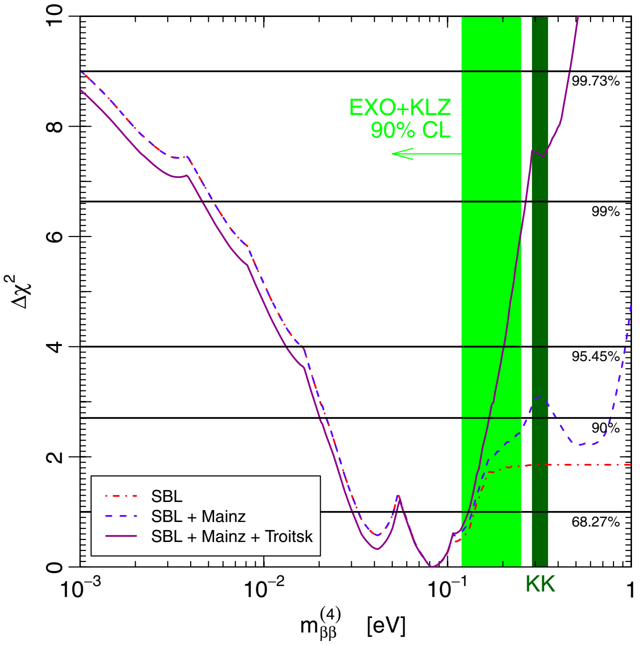

FIG. 3 (color online). Marginal $\Delta\chi^2$ as a function of $m_{\beta\beta}^{(4)}$ obtained from the fit of ν_e and $\bar{\nu}_e$ short-baseline oscillation data (dash-dotted curve), from the combined fit of oscillation and Mainz data (dashed curve), and from the combined fit of oscillation, Mainz and Troitsk data (solid curve). The vertical green band represents the currently most stringent upper bound for $m_{\beta\beta}^{(4)}$ in the no-cancellation case (see text) given by the combined EXO and KamLAND-Zen 90% CL bound on $m_{\beta\beta}$, taking into account nuclear matrix element uncertainties [73]. The vertical dark-green band corresponds to the 1σ Klapdor-Kleingrothaus *et al.* range of $m_{\beta\beta}$ [77].

Let us also notice that the marginal $\Delta\chi^2$ for $\sin^2 2\vartheta_{ee}$ in Fig. 2 is similar to that obtained in Ref. [7] from short-baseline data alone. It gives the interesting interval

$$0.05 \lesssim \sin^2 2\vartheta_{ee} \lesssim 0.19 \qquad (2\sigma), \tag{9}$$

which is testable in future short-baseline experiments with electron neutrino and antineutrino radioactive sources [47,51–58,66], reactor electron antineutrinos [47,62–65], and accelerator electron neutrinos [59–61].

The bounds on $\sin^2 2\vartheta_{ee}$ and Δm_{41}^2 that we have obtained allow us to update the predictions of Ref. [7] for the contribution $m_{\beta\beta}^{(4)} \simeq |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$ of ν_4 to the effective Majorana mass in neutrinoless double-β decay. Figure 3 shows the marginal $\Delta\chi^2$ as a function of $m_{\beta\beta}^{(4)}$ obtained from the fit of short-baseline oscillation data in Ref. [7] (dash-dotted curve). One can see that in this case, $m_{\beta\beta}^{(4)}$ has no upper bound at 83% CL. The dashed curve in Fig. 3, obtained from the combined fit of oscillation and Mainz data, gives an upper bound for $m_{\beta\beta}^{(4)}$ of 0.91 at 2σ. The solid curve in Fig. 3, obtained with the addition of Troitsk data, improves dramatically the bound, because the marginal

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[3] Similar considerations apply to the IsoDAR proposal in Ref. [66].

$\Delta\chi^2$ increases steeply for $m_{\beta\beta}^{(4)}$ larger than the best-fit value at about 0.08 eV. Considering also the lower bound for $m_{\beta\beta}^{(4)}$ given by short-baseline oscillation data alone, we obtain

$$0.013 \lesssim m_{\beta\beta}^{(4)} \lesssim 0.20 \text{ eV} \qquad (2\sigma). \tag{10}$$

The slight decrease of the marginal $\Delta\chi^2$ for $m_{\beta\beta}^{(4)}$ smaller than the best-fit value obtained with the inclusion of Troitsk data is due to a slight increase in the value of χ^2_{min}, from 45.5 to 45.8.

Considering the case in which the contribution $m_{\beta\beta}^{(4)}$ to the effective Majorana mass is not canceled by that of the three light neutrinos (i.e., $m_{\beta\beta} \geq m_{\beta\beta}^{(4)}$; see the discussion in Ref. [7] and Refs. [71,72]), Fig. 3 also shows the currently most stringent 90% CL upper bound for $m_{\beta\beta}$ obtained in Ref. [73] from the combined EXO [74] and KamLAND-Zen [73] data, taking into account nuclear matrix element uncertainties. One can see that this upper bound erodes the upper bound in Eq. (10) for large values of the nuclear matrix element. The interesting range of $m_{\beta\beta}^{(4)}$ below the EXO + KamLAND-Zen upper bound will be explored by several neutrinoless double-β decay experiments in the near future (see Refs. [75,76]).

Figure 3 shows also the 1σ Klapdor-Kleingrothaus *et al.* range of $m_{\beta\beta}$ [77]. Besides being disfavored by the EXO + KamLAND-Zen upper bound on $m_{\beta\beta}$, it is also disfavored by our results if $m_{\beta\beta}^{(4)}$ is the dominant contribution to the effective Majorana mass and if there is a cancellation of $m_{\beta\beta}^{(4)}$ with the contribution to the effective Majorana mass of the three light neutrinos [7,71,72], i.e., if $m_{\beta\beta} \leq m_{\beta\beta}^{(4)}$.

In conclusion, we have obtained an interesting upper bound for Δm^2_{41} in the framework of 3 + 1 mixing from the results of short-baseline ν_e and $\bar{\nu}_e$ oscillation data and from the recent results of a search for the effects of m_4^2 in the spectrum of the electrons emitted in Tritium decay in the Troitsk nu-mass experiment. The upper bound for Δm^2_{41} implies that it is likely that the electron neutrino oscillation length is sufficiently large to measure the dependence of the disappearance probability as a function of distance and/or energy in electron neutrino and antineutrino radioactive source experiments. It is also favorable for the proposed ICARUS@CERN experiment, because it implies that it is likely that oscillations are not washed out in the near detector. We have also discussed the implications of our results for neutrinoless double-β decay.

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